Agroforest Syst (2014) 88:1001–1019
DOI 10.1007/s10457-014-9692-7

Cocoa–timber agroforestry systems: *Theobroma cacao–Cordia alliodora* in Central America

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Received: 9 September 2013 / Accepted: 15 March 2014 / Published online: 28 March 2014

Abstract Cocoa–timber systems have been proposed as viable alternative for simultaneously satisfying the livelihood needs of the farmers (in terms of production of cocoa and other goods for family use or sale) while improving the capacity of the cocoa agroforestry system to provide other ecosystem services at both the plot and landscape level. In this paper we explored the demographics, population dynamics and timber yield of naturally regenerated laurel (*Cordia alliodora* R&P Oken) in 33 ha of cocoa plantations (42 farms) inventoried in 2001 and remeasured in 2005 and 2011, in Talamanca, Costa Rica. This study shows in quantitative terms the significant contribution of laurel timber in the shade canopy of cocoa to annual income (use or sale of timber) and family savings (timber in standing, harvestable trees). In the study region, laurel yields 4.43 m^3 ha^{-1} $year^{-1}$, equivalent to an annual income of 265 US$ ha^{-1} $year^{-1}$ (assuming that 50 % of total standing volume is saleable, at 120 US$ m^{-3} for standing laurel timber at the farm). In addition to the cash flow, standing, harvestable laurel trees (43.89 m^3 ha^{-1}) amounts to 2,633 US$ ha^{-1} in family savings.

Keywords Population projection matrix · Growth · Mortality · Diameter frequency distribution · Timber yield · Basal area

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Introduction

Cocoa is cultivated by 5 million rural families (mostly smallholders with farms <5 ha) over some 7 million

hectares of land (www.worldcocoafoundation.org). Most cocoa is grown under a tree shade canopy. For example, in Latin America 70 % of the 1.5 million hectares cultivated with cocoa are under shade (Somarriba et al. 2012a). In Ghana and Ivory Coast, shaded cocoa accounts for 71–72 % of total area under cultivation; shaded cocoa is highly prevalent, 92–98 %, in Cameroon and Nigeria (Asare 2005; Gockowski and Sonwa 2008, 2011). Smallholders use shade trees to shelter cocoa plants, regulate cocoa productivity (e.g. improving soil fertility and adjusting shade levels to soil fertility status), and to produce other valuable goods (timber, fruits, construction materials, medicine, etc.) for household consumption, farm use or sale (Beer et al. 1998; Cerda et al. 2014; Duguma et al. 2001; Gockowski and Sonwa 2008; Herzog 1994; Laird et al. 2007; Leakey and Tchoundjeu 2001; Rice and Greenberg 2000). Farmers have a rich knowledge on the biology, management and use of numerous tree species present in the shade canopy of cocoa (Asare 2005; Anglaaere 2005; Bentley et al. 2004; Gyau et al. 2014; Nomo 2005; Ortíz-González 2006; Silva et al. 2013; Smith et al. 2014).

Timber trees are a frequent component in cocoa shade canopies and various authors have recommended cocoa–timber systems to increase the sustainability and financial efficiency of cocoa farming (Ofori-Bah and Asafu-Adjaye 2011; Gockowski and Sonwa 2011; Ruf 2011; Somarriba and Beer 2011), and as a viable strategy for the intensification of cocoa cultivation compatible with the conservation of biodiversity, provision of ecosystem services, and the conservation of natural forests at the landscape level (Clough et al. 2010; Gockowski and Sonwa 2011; Schroth et al. 2011; Steffan-Dewenter et al. 2007; Tscharntke et al. 2010; Wade et al. 2010). However, solid, quantitative information on the stocks, growth and yield of cocoa–timber agroforestry systems is both scanty and fragmentary.

Many studies of cocoa shade canopies provide species lists and indication of use (e.g. timber, fruit, restoration of soil fertility, medicine, etc.), but when use is reported, little quantitative data is provided on population size, diameter distribution, and growth or yield of timber. Some knowledge is, however, available. Various studies have documented the contribution of timber from cocoa shade canopies to: (1) satisfy the construction needs of the household; (2) cope with un-expected family needs (timber trees as a saving account, a safe net); (3) generate additional income, crucial at times of low cocoa prices or when new diseases strike cocoa; (4) diversify family income and reduce financial risk; and (5) increase the value of the land (Alger and Caldas 1994; Asase and Tetteh 2010; Cerda et al. 2014; Herzog 1994; Navarro and Bermúdez-Cruz 2009; Obiri et al. 2007; Orozco 2005; Ramírez et al. 2001; Rosemberg and Marcotte 2005). Other studies have looked at the transformation of an existing (allegedly un-productive or inadequate) shade canopy into a regulated, productive one, by planting timber trees and gradually removing (selectively or totally) the original canopy trees (Hernández and von Platen 1994; Matos 1999; Navarro and Bermúdez-Cruz 2009; Somarriba 1994; Somarriba and Domínguez 1994). Cocoa–plantain–*Cordia alliodora* systems have been evaluated in Panama (Calvo and von Platen 1996; Ramírez et al. 2001) and in Colombia (Aristizábal-Hernández et al. 2002). The damage inflicted to cocoa during the harvest of the timber (a concern for farmers and extension workers alike) has been measured in one study, and found it not to be as severe as expected (the income from timber sales easily offset the costs of the damage); damage to cocoa due to the harvest of timber should not be an argument to constraint the promotion and use of timber trees in cocoa production (Ryan et al. 2009). Manuals for extension officers and farmers describing how to design and manage cocoa-timber plantations have been prepared for Honduras (FHIA 2004).

Timber trees in cocoa shade canopies may be planted (Aristizábal-Hernández et al. 2002; Chalmers 1971; Egbe and Adenikinju 1990; FHIA 2007; Orozco 2005; Quispe 2006; Ramírez et al. 2001; Sánchez-Gutierrez 2012; Vásquez-Tarrillo et al. 2008), remnants of the native forest, either primary and secondary (Lobao and Valeri 2009; Rolim and Chiarello 2004; Sambuichi 2002, 2006; Sambuichi and Haridasan 2007; Sonwa et al. 2007; Zapfack et al. 2002); or recruited from natural regeneration. Naturally regenerated timber species present in cocoa shade canopies belong to a small group of successfully reproducing, native species representatives of the local flora.

Naturally regenerated timber trees typically occur at low population densities (5–20 trees ha^{-1}) in mixed cocoa shade canopies, (Asase et al. 2009; Asase and Tetteh 2010; Bobo et al. 2006; Chalmers 1971; Coello-Arechúa and Haro-Cambo 2012; Laird et al. 2007; Mussak and Laarman 1987; Orozco 2005;

Quispe 2006; Roa-Romero et al. 2009; Sáenz-Tijerino 2012; Salgado-Mora et al. 2007; Suárez-Islas 2001; Suatunce 2002; Sambuichi 2002, 2006; Sonwa et al. 2007; Vásquez-Tarrillo et al. 2008). In certain regions, however, one or a few timber species (mostly long-lived pioneers), successfully adapted to the agricultural and land use cycles in the landscape, maintain viable populations with high planting densities over long periods of time. Notorious examples include the complex *Tabebuia neochrysanta–Triplaris cumingiana–Schizolobium parahyba–C. alliodora* in coastal Ecuador (Bentley et al. 2004; Mussak and Laarman 1989), *Guazuma crinita* in Peru (Vásquez-Tarrillo et al. 2008), *C. alliodora–Cedrela odorata* in Central America (Cerda et al. 2014; Niehaus 2011; Sáenz-Tijerino 2012; Suárez-Islas 2001; Van Bael et al. 2007), and *Terminalia ivorensis–Terminalia superba* in West and Central Africa (Anglaaere 2005; Asare 2005; Gockowski and Sonwa 2008; Nomo 2005; Sonwa et al. 2007).

In this paper we explored the demographics, population dynamics and timber yield of naturally regenerated laurel (*C. alliodora* R&P Oken) in small cocoa plantations in indigenous Talamanca, Costa Rica. We modeled the changes in population density, basal area, and standing timber volume of laurel using a transition probability projection model (Vanclay 1995), and explored different approaches to estimate diameter increment, mortality and recruitment rates. We compared our diameter growth results with a comprehensive bibliography (including a large body of “grey literature”) reporting on age, size and growth of laurel in Latin America. Most cited literature is available at http://biblioteca.catie.ac.cr/inaforesta. A representative model for laurel in cocoa plantations in Talamanca, Costa Rica was used to estimate stocks and yield of timber.

Laurel is a fast-growing tree with a high-quality wood for furniture making. The species is widely distributed in continental tropical America from central Mexico to northern Argentina, including the Caribbean islands, a range in latitude of some 50°, from approximately 25°N to 25°S. Laurel produces high-quality timber and the tall, straight stem, self-pruning habit, and compact crown makes it suitable for growing it in combination with many agricultural crops. This, combined with the easiness with which laurel regenerates naturally on cleared sites, has led to its presence in numerous agroforestry systems throughout its natural range (CATIE 1994; Greaves and McCarter 1990). Laurel is the most abundant species in cocoa shade canopies in Central America (Almendárez et al. 2013; Cerda et al. 2014; Matey et al. 2013; Sáenz-Tijerino 2012; Van Bael et al. 2007) and in Chiapas, Mexico (Salgado-Mora et al. 2007).

Materials and methods

Definitions, terms and concepts

A farm is the land unit (in a single block or not) managed by the family or firm. The farm includes several cropping systems, one of which may be cocoa. A cocoa plantation is a single block of land, of variable size and form, dedicated to cultivating cocoa with or without other associated plants. A cocoa plantation has two components: cocoa and shade canopy. The cocoa component includes all cocoa plants; since all cocoa trees are of similar size their crowns form a cocoa canopy. The shade canopy is a volume, a 3-dimensional space with base equal to the area and shape of the land covered by the plantation, and height equal to the height of the tallest tree in the plantation. The shade canopy includes all non-cocoa plants taller than cocoa; trees dominate most shade canopies. A cocoa shade canopy may include groups of plant species that produce one or more goods and services, for instance, timber, fruit, medicine, aesthetic and cultural values, conservation of nature, etc. A tree is composed of bole and crown. As young cocoa trees grow in height and crown size, upper leaves shade those underneath, producing self-shading; in crowded conditions, neighbor cocoa trees cast shade on each other and this is also considered as self-shading. The site is the set of biophysical conditions (soil, climate, biology and local culture) that determines the upper limits to the growth and yield of both cocoa and the shade canopy. A cocoa growing area is the territory containing the cocoa farms. A stand denotes all the trees in the cocoa plantation. Various stand density measures (population, basal area and total stem wood volume) are used to describe the stocking of the stand. Stocking denotes the degree of utilization of the space and other resources of the site, in reference to a desirable maximum (or optimum). Population density refers to counts of individuals over a reference plantation area (n ha^{-1}). Basal area is the summation of the sectional

areas of the stems (at given height above ground) of all plants in a reference plantation area (m^2 ha^{-1}). Stand density and stocking may be calculated for the cocoa, the shade canopy, and the plantation. Weeding denotes the removal of small trees by farmers when tending the plantation, or by natural processes. In this study, weeding regulates the density of laurel trees with stem diameter at breast height, $D < 5$ cm. Laurel mortality due to weeding (with direct impacts on laurel recruitment rates) was not considered in this study. Thinning is the reduction in the number of small and medium sized laurel trees ($5 \leq D \leq 30$ cm) between two consecutive measurements. The disappearance of a tree between consecutive measurements may be due to either pure mortality (e.g. disease, breakage due to wind or fallen branches from taller, neighbor trees) or removal by the farmer to regulate shade or tree density. Our field measurements can't separate thinning from true mortality. In this paper, we use the term "thinning" to denote the combination of thinning and true mortality of laurel trees with $5 \leq D \leq 30$ cm. Harvest refers to the felling of trees with $D > 30$ cm. Weeding, thinning and harvest are the sources of "mortality" for laurel trees in the cocoa plantation.

The study area

The Bribri and Cabécar indigenous territories (43,690 and 22,729 ha, respectively, for a total 66,419 ha) are located in Talamanca, Limon, Costa Rica, between 9°21′38″ and 9°31′30″ N, and 82°54′40″ and 83°50′40″ W. The landscape includes the floodplains of the Talamanca Valley (60–120 m altitude), surrounded by undulating foothills (below 500 m altitude) that give way to the highlands of the Talamanca mountain range. The average daily temperature of the region is 25.8 °C and average annual precipitation 2,370 mm, with short dry seasons in March–April and in September–October (Herrera 1985). Both territories support a total population of about 10 000 inhabitants (15 inhabitants per km^2). The major sources of income to the households are the cultivation of plantain, organic banana and organic cocoa, and wage labor. Agricultural land covers some 17,000 ha, 60 % of it in the valley. Cocoa figures prominently in the Bribri and Cabécar narratives of origin and in ceremonies (Borge-Carvajal 2011).

The Talamanca valley contains highly variable Entisols, fertile with high base status and high organic matter content (Polidoro 2007). Soils exhibit the general trends of increasing organic matter and clay, and decreasing sand in downstream areas and in increasing distance from rivers. Clays are mostly smectite, with some vermiculite and kaolinite. Average C:N ratio is 8.75 ± 1.3. Soil properties in the Talamanca floodplain are largely driven by smectitic clay mineralogy and dynamic hydrologic processes (Polidoro 2007). In contrast, the foothills are a mosaic of acidic, low-fertility soils with high clay content, classified as Ultisols, intermixed with less acidic, slightly more fertile soils, classified as Inceptisols (Winowiecki 2008). Typic Hapludults occupy both ridgetop and midslope landscape positions, Typic Dystrudepts and Dystric Eutrudepts occupy the foot slopes, and Udifluvents and Fluventic Eutrudepts occupy the floodplain. Total Si, Ca, and K contents increase downslope; pH varies between 3.0 and 6.3 (Winowiecki 2008). Variations in soil type and slope have contributed to the current pattern of land use in Talamanca: banana and plantains in the fertile soils in the valley, and cocoa on the low-fertility soils of the foothill slopes; some cocoa is cultivated in the valley, close to the foothills (Dahlquist et al. 2007).

Households and cocoa plantations (cocoa + shade canopy)

Households cultivate various plots scattered in the landscape; land holdings in the valley are generally much smaller than those in the foothills (Whelan 2005). In the valley, farm sizes range between 10 and 15 ha, and area under cocoa cultivation is 2.5 ± 1.3 ha; forest patches cover 47–52 % of farm land; cocoa covers 20 % of farm land. Foothill farmers practice slash and burn (or slash-and-rot) cultivation of annual crops, retain significant amounts of primary and old secondary forest patches in the farm land, and cultivate cocoa in association with banana and laurel (Orozco et al. 2008; Somarriba et al. 2003).

The botanical composition of cocoa shade canopies in Talamanca is dominated by laurel in association with palms (*Bactris gasipaes* and *Iriartea deltoidea*), fruit trees (*Spondias mombin*, *Citrus* spp., *Cocos nucifera*, *Persea americana, Nephelium lappaceum*), service legume trees such as *Inga* spp., and other naturally regenerated, valuable timber species such as *Cedrela odorata, Terminalia oblonga, Hyeronima alchorneoides* and *Chloroleucon eurycyclum* at low

planting densities (Deheuvels et al. 2012; Guiracocha Freire 2000; Orozco et al. 2008; Somarriba et al. 2003; Suatunce 2002). A study of four types of cocoa shade canopies, ordered in a decreasing trend of structural complexity [(1) laurel—native trees, (2) laurel—fruit trees, (3) laurel—banana and (4) laurel—*Inga edulis*] showed marked differences between types in terms of the number of botanical families (21, 18, 12, 2), genera (32, 22, 16, 2), species (38, 27, 17, 2) and basal area (25.6, 12.8, 8.1 and 9.3 m^2 ha^{-1}). Population density, however, did not differ between types (148, 156, 163 and 120 trees ha^{-1}) (Suatunce 2002). Farms in the Talamanca foothills stock more carbon (40.54 Mg ha^{-1}) than farms in the valley (31.49 Mg ha^{-1}) (Arce-Hernández 2006).

Field data

Cocoa and tree inventory data from various studies (Arce-Hernández 2006; CATIE un-published; Cerda et al. 2014, this volume; Suatunce 2002), including laurel diameter data for 2011 from this study, were pooled into two files: (A) stand density data for cocoa, laurel and other plants in the shade canopy (177 plots in same number of farms, 10.9 ha of inventories in 2005 and 2011), and (B) laurel diameter frequency distribution data from 466 farms, 109.4 ha of inventory, and 5,376 laurel trees measured in 2006 and 2011.

The demographics of laurel was studied in a sample of 65 cocoa farmers randomly selected in 2001 from the roster of 761 members of APPTA (Asociación de Pequeños Productores de Talamanca), the major farmers' cocoa cooperative in Talamanca (Suárez-Islas 2001); 42 of the selected farms had cocoa as the main crop; 24 farms had plantains or bananas as dominant crops. This study includes only the 42 cocoa farms. A map of every cocoa plantation was prepared using a theodolite to accurately estimate area and tree density; total inventory area was 33.61 ha. Stem diameter at 1.3 m above the ground (D) of all laurel trees was measured in each plot in 2001, 2005 and 2011. Farmers are only concerned with the population numbers of laurel young trees that out-grow the cocoa canopy (4–5 m height), which typically occurs when D reaches 5 cm in Talamanca.

Trees were not tagged and numbered in 2001, but their locations were marked in the map so they could be easily re-located in future re-measurements (Suárez-Islas 2001). All trees measured in 2005 (those measured in 2001 who survived until 2005 + new recruits) were numbered and tagged (Calero-Borge 2008). All farms were re-measured in 2011 and new recruits numbered and tagged. Re-measurement data was used to estimate annual D increments (by tree or by D class), mortality, thinning, and recruitment rates by D class (5 cm interval). In each inventory, all laurel stumps (indicative that a tree was thinned out to regulate shade, or harvested for lumber) were inspected along with the farmer, the diameter of the stem measured (avoiding and/or adjusting for deformities due to buttresses, and assumed equal to D), and the year of harvest recorded. Farmers were able to date back tree harvest up to 4 years in the past. A comprehensive data file of stump data by farm, year of harvest, and D at harvest was constructed and used to estimate the annual rate of tree thinning and harvest by D class.

Data analysis

Four levels of data analysis were used: (1) stand density measures for cocoa plantations, fractioned by cacao, laurel and other trees in the shade canopy; (2) laurel density measures by farm; (3) laurel demographics, and (4) simulations. Average population density, basal area, and standing timber volume in cocoa, laurel and other shade canopy plants were calculated using pooled data. In the study on the demographics of laurel, tree measurements were screened for errors; trees included in the analysis met the following criteria: (1) D increased between successive measurements; (2) D mean periodic increment $I \leq 10$ cm $year^{-1}$ for trees with $D < 10$ cm; (3) $I \leq 7$ cm $year^{-1}$ for trees with $10 < D \leq 20$ cm; (4) $I \leq 5$ cm $year^{-1}$ for trees with $20 < D \leq 30$ cm; and (5) $I \leq 3$ cm $year^{-1}$ for trees with $D > 30$ cm. A total of 803 trees met these criteria in the period 2001–2005, and 825 in 2005–2011, for a great total of 1,628 trees with D re-measurements. Field data included: date of measurement (year), cocoa plot #, tree #, measured D, and status (a flag to indicate whether the tree was being re-measured or it was a new recruit in the population). In what follows we present the details of the estimation of: (1) population size and structure (various stand density measures and D frequency distributions), (2) annual periodic increments in D, (3) per tree rates of mortality, thinning and harvest; (4) annual recruitment; and (5) transition

probability coefficients; (6) population projections and simulations.

Laurel density by farm

Seven stand density measures were used to describe the stocking of the shade canopy stand, and then compared between inventory years using a mixed, linear, generalized model, with farms as random effects, and plantation area as co-variable. Means were compared with Fisher's LSD, $\alpha = 0.05$. Stand density measures included: mean D (cm); population density (n ha^{-1}); basal area (g, m^2 ha^{-1}); and total, over-bark, stem volume (m^3 ha^{-1}) for all (nTotal, gTotal, vTotal) and harvestable laurel trees (D >40 cm, denoted as nD40, gD40, vD40) Frequency distributions for each stand density measure were described with Weibull functions (Rinne 2009). Average D (weighted by D class frequency) was calculated and inter-year comparisons made with a t test. The probability density function (Y_1) and the cumulative density function (Y_2) of the Weibull function are:

$$Y_1 = \left[(k/\lambda)(D/\lambda)^{k-1}\right] \cdot e^{-\left[(D/\lambda)^k\right]} \quad (1)$$

$$Y_2 = 1 - e^{-\left[(D/\lambda)^k\right]} \quad (2)$$

with D = stem diameter at breast height (1.3 m aboveground), in cm; k shape and λ scale parameters.

Diameter frequency distributions

Tree D data by inventory year ($n_{2001} = 2{,}187$ trees, $n_{2005} = 2{,}427$ and $n_{2011} = 2{,}036$) was sorted into 5 cm interval D classes and the frequencies by class determined. Pooled data was used to estimate the representative diameter frequency distribution for laurel in the shade canopy of cocoa in Talamanca. Weibull functions were fitted to describe the data. Frequency distributions were compared with Kolmogorov–Smirnov tests.

D annual periodic increment (I) and transition coefficients

The mean, annual periodic D increment (I, cm $year^{-1}$) by tree ($n = 1{,}628$) was calculated as the difference in D between two consecutive measurements, divided by the number of years between measurements. Trees were sorted into 5 cm interval D classes according to initial D and average *I* by D class calculated. An exponential regression model of the form:

$$I = a \cdot Log(G) + b \quad (3)$$

was fitted to average I by D class data. A diameter-age curve was generated by simulations using D periodic increments by tree; a modified version of the algorithm proposed by Lieberman and Lieberman (1985) was used in the simulations. In our study we used a fixed, contiguous sampling frame instead of a movable one, with trees ordered in ascending annual periodic increment within the D class. This procedure makes it simpler to determine the D-age trajectories for the slowest and fastest trees, and generates "smoother" D-age trajectories than with a movable frame. A Chapman-Richards function (Zeide 1993) was fitted to the simulated D-Age data.

$$D = a \cdot (1 - e^{-b \cdot Age})^c \quad (4)$$

Transition coefficients between two adjacent D classes were estimated with two alternative procedures: (1) using average D increments by D class and assuming that trees were evenly distributed in the class interval; and (2) using D increment by tree to project tree D into the future, and trees at their current position within the D class interval. In procedure #1, the time it takes to one tree in a given D class to transit the width interval of the class *i* (T_i) was calculated as:

T_i = (W_i, interval width of class *i*, cm)/(I_i, mean annual diameter increment in class class *i*, cm $year^{-1}$)

$$T_i = \frac{(Wi)}{(Ii)}$$

Without adjusting for tree mortality, the fraction ($P_{i,\,i+1}$) of individuals in class D_i that move on to class $D_{i\,+\,1}$ after 1 year, is given by the reciprocal of T_i.

$$P_{i,i+1} = {}^{1}\!/_{T_i} = {}^{Ii}\!/_{W_i}$$

In procedure #2, transition coefficients were estimated in a two steps process. First, we projected tree D over a 5 year period (mortality not considered) by adding five times the D increment measured to the initial D; each year, both initial and final D was coded with their corresponding D class. Five pairs of D data for 1,628 trees generated 8,140 registers containing D class positions at time t and t + 1. The following

algorithm kept track of the transitions of laurel trees between D classes:

$$X_n^i = \text{Status of tree } i \text{ in year } n\ (n = 2001, \ldots, 2011)$$
$$m = D\,\text{classes}\ (m = 1, 2, \ldots, 15)$$

We kept track of the transitions of tree i between D classes after 1 year of growth with the variable ZT:

$$ZT^i_{m,m+q} = \begin{cases} 1 & \text{if } X_n^i = m \text{ and } X_{n+1}^i = m + q \\ 0 & \text{if } X_n^i = m \text{ and } X_{n+1}^i = m \end{cases}$$

The variable "C, kept track of the status m of tree i in year n":

$$C_m^i = \begin{cases} 1, & \text{if } X_n^i = m \\ 0, & \text{if } X_n^i \neq m \end{cases}$$

Then the transition probability from D class $m \to m + q$ was given by:

$$P(m, m+q) = \sum_n \frac{\sum_i ZT^i_{m,m+q}}{\sum_i C_m^i}$$

with $m = 1,2,\ldots,15$, $q = 0,1,\ldots,15 - m$, and $n = 2001,\ldots$

Weeding, thinning (+mortality) and harvest

Per tree, annual rate of thinning by D class was estimated from mortality counts between successive inventories, divided by total initial population size by D class (dead + alive). The annual rate of tree harvest by D class was obtained by dividing the number of stumps in class D in a given year, by the total number of trees (standing + stumps) in class D in the population that year.

Transition matrices, simulations, estimation of recruitment rates

Thinning and harvest rate, and average increments by D class were used to construct a population transition matrix without specifying a recruitment rate. Our field data did not provide an accurate estimate of the annual recruitment rate because D increments are large in small, young laurel plants and any thinning or natural mortality would go unnoticed between two consecutive measurements 5 years apart. Using simulations, we estimated the recruitment rates that would project the population size (nTotal and nD40) and structure (D frequency distribution) observed in 2001 into the population size and structure observed in 2011. We compared D frequency distributions using the Kolmogorov–Smirnov test.

A model representative of the population dynamics of laurel in the cocoa - timber production system of Talamanca was constructed using: (1) average annual periodic increment by D class using Eq. 3 to estimate transition coefficients, (2) the representative D frequency distribution of laurel in Talamanca as described by a Weibull function, (3) thinning and harvest rates determined from field measurements, and (4) recruitment rate estimated by simulations. We used this model to: (1) estimate the standing stock and the expected annual yield of timber in the next 5 years, and (2) explore the effect of the observed D frequency distribution by farm in 2001 on both stocks and yields timber. To evaluate the later, we adjusted to one hectare the D distribution observed in 2001 and projected the population until 2011; we recorded the volume of wood harvested in the period and stock in standing timber at the end of the 10 year period. We used scatter plots and linear correlations to explore the relationship between stand density measures in 2001 and both timber harvest and standing stock of timber at the end of the simulation period. We estimated total timber volume by tree (Somarriba and Beer 1987) using:

$$V = e^{[-9{,}62 + 2{,}697 \cdot Ln(D)]} \tag{5}$$

with V = total over-bark stem volume in m^3 $tree^{-1}$; e = base of natural logarithms (ln); D is trunk diameter at 1.3 m aboveground, in cm.

Results

Cocoa plantations: density of cocoa and shade trees

A typical cocoa plantation in Talamanca had a total basal area of 16.54 m^2 ha^{-1}, with 7.23 allocated to cocoa and 9.31 to the shade canopy. Laurel accounts for 3.91 m^2 ha^{-1} (42 %) of the basal area in the shade canopy. Other trees accounts for the remaining 5.4 m^2 ha^{-1} (Table 1). In terms of population numbers, cocoa plantations include 475 cocoa trees ha^{-1} and 149 trees ha^{-1} in the shade canopy, for a total density of 624 plants ha^{-1} in the plantation. Laurel

Table 1 Population density and basal area in cocoa (*Theobroma cacao*), laurel (*Cordia alliodora*) and other trees in the shade canopy of cocoa plantations in Talamanca, Costa Rica. Shade canopy = laurel + others; Plantation = cocoa + shade canopy

Parameter	Component	Mean ± SD	Median
Population (trees ha^{-1})	Cocoa	475 ± 211	460
	Laurel	48 ± 47	40
	Others	101 ± 84	80
	Shade canopy	149 ± 93	130
	Plantation	624 ± 248	600
Basal area (m^2 ha^{-1})	Cocoa	7.23 ± 3.73	6.67
	Laurel	3.91 ± 3.99	3.16
	Others	5.4 ± 6.07	4.01
	Shade canopy	9.31 ± 6.68	7.98
	Plantation	16.54 ± 7.81	15.76

account for 48 trees ha^{-1}; and 101 trees ha^{-1} in the shade canopy belong to other species.

The density of laurel in the shade canopy

The basal area and standing timber volume of laurel (total and harvestable) increased steadily between 2001 and 2011: from 17 to 44 m^3 ha^{-1} in timber and from1.97 to 4.11 m^2 ha^{-1} in basal area (Table 2). Unlike basal area and timber volume, the total number of trees per hectare did not vary significantly in the study period (Table 2). Average D for laurel remained between 28.0 and 28.6 cm between 2001 and 2011, but due to low standard errors (0.03 any year), weighted mean D was statistically similar between 2005 and 2011, and both different to 2001 (28.6 cm). Weighted mean D for Talamanca was estimated at 28.85 cm (Table 2). Stand density measures were not affected by the area of the cocoa plantation.

The diameter frequency distribution of laurel

The diameter frequency distribution of laurel in Talamanca is mono-modal, with a "hump" at 30 cm (Fig. 1); a Weibull function described the data very well, with low standard errors (Table 3). The frequency distributions of laurel inventoried in 2001, 2005 and 2011 had the same shape as the Talamanca distribution, with a hump around the 30 cm diameter class (Table 3). Despite this similarity, all frequency distributions were statistically different between them (Kolmogorov–Smirnov, KS, $p < 0.01$). The shape of the diameter frequency of laurel in Talamanca is roughly similar to the ones observed in Central America (Table 4).

Mean periodic increment in D

Average D increment (I) decreased as D increased, from 4.7 cm year^{-1} for small trees with D <5 cm to 0.46 cm year^{-1} in large trees with D ≥70 cm. An exponential model fitted (Eq. 6) data very well ($R^2 = 0.81$), with well distributed residuals, and statistically significant ($p < 0.0001$) model and regression coefficients (Fig. 2; Table 5).

$$I = 5.69 - 1.14 \cdot Ln(D) \tag{6}$$

with I in cm year^{-1}, ln is natural logarithms, and D is stem diameter at 1.3 m aboveground, in cm.

Average, annual periodic D increments observed and estimated by regression were similar (Spearman,

Table 2 The population density, basal area, and total over-bark stem volume of naturally regenerated *Cordia alliodora* trees in the shade canopy of cocoa plantations, Talamanca, Costa Rica)

Sample	Mean diameter (cm)	Population (n ha^{-1})		Basal area (m^2 ha^{-1})		Timber volume (m^3 ha^{-1})	
		Total	D >40	Total	D >40	Total	D >40
2001	28.6^a	44.90^{ns}	5.90	1.97	1.13	16.78	6.08
2005	28.0^b	52.36^{ns}	8.29	2.69	1.55	27.84	11.30
2011	28.1^b	53.41^{ns}	14.78	4.11	2.93	43.67	25.92
Talamanca	28.85	47.81	23.5	4.36	3.48	48.23	43.89

Results are presented for both the total and harvestable (stem diameter, D >40 cm) populations of laurel inventoried years 2001, 2005 and 2011. An estimate for laurel in the shade canopy of cocoa in Talamanca region is also included. ns = values in the same column are not statistically different; different letter in the same columns indicates statistically different values

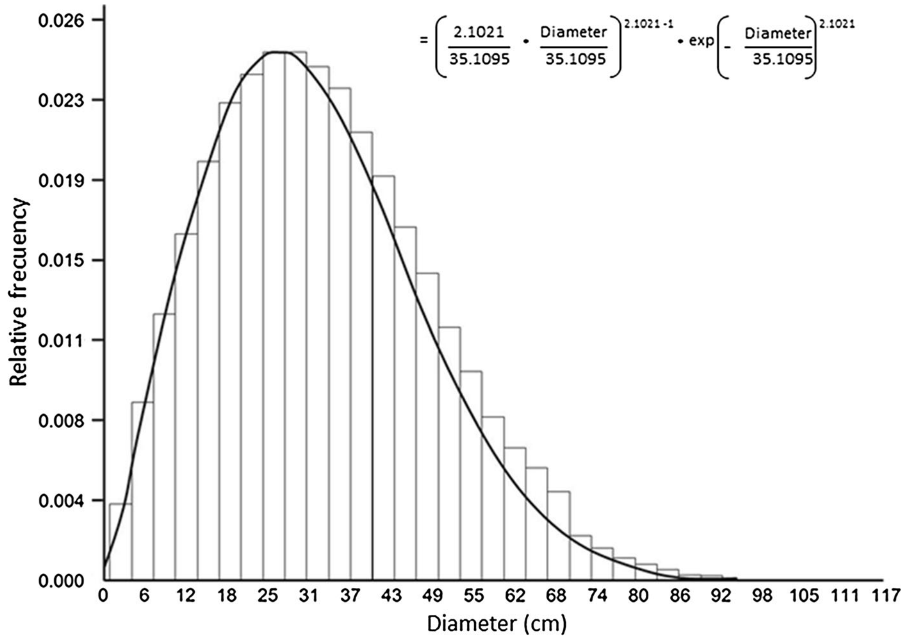

Fig. 1 Probability density function (Weibull) of *Cordia alliodora* trees by stem diameter. Cocoa shade canopies, Talamanca, Costa Rica. Data file B, see "Materials and methods" section

r = 0.98, $p < 0.0001$), but the regression under-estimated I for trees with D <20 cm (Fig. 3). Transition probability coefficients derived from Eq. 6 were lower than those derived from measured averages or projected increments by tree (Fig. 2). Correlations coefficients between these three estimates were high and statistically significant (r 0.97–0.99, $p < 0.001$). Population projections were then made using transition probabilities predicted by Eq. 6.

The average D–A trajectories obtained from simulations using periodic increment data were properly described by a Chapman-Richards function (Eq. 7, Fig. 3); all coefficients were statistically significant ($p < 0.001$), with low standard errors (0.0016, 0.0002 and 0.001 for each coefficient in the equation). The range of simulated growth trajectories gives us an idea of the range of ages for a given harvest diameter. For instance, it may take 15 years to reach 40 cm in D to a fast growing tree (sprinters), but it will take 26 years to reach this size to a slow-growing (sluggish) tree.

$$Ln(D) = 4.66 \cdot (1 - e^{-0.067 \cdot A})^{0.51} \quad (7)$$

with Ln natural logarithm, D stem diameter in cm, and A age in years.

Thinning-mortality and harvest annual rates

Laurel population numbers are regulated by farmers through weeding (seedlings, saplings and small poles with D ≤5 cm), thinning between 5 and 25 cm, and harvest of trees 25–70 cm in D (Fig. 4). Thinning rates decreased from 14 % for small trees to 2 % for big trees; on the contrary, harvest rate increased roughly from 2 % for D between 25 and 30 cm to 18 % for trees >65 cm in D (Table 6).

Recruitment rate

An estimated annual recruitment rate of 3.2 recruits ha^{-1} $year^{-1}$ projects, with good fit, the D frequency distribution observed in 2001 to the one observed in 2011. Observed and predicted population structures were statistically non-significant (Kolmogorov–Smirnov distance, KS) for a range of recruitment rates between 0 and 43 recruits. The typical humped distribution of laurel is reproduced with recruitment rates between 5 and 7 recruits ha^{-1} $year^{-1}$ (Fig. 5).

Table 3 Diameter (D) frequency distribution of *Cordia alliodora* trees by diameter class in cocoa shade canopies in Talamanca, Costa Rica. Coefficients for Weibull functions are provided

D class upper limit (cm)	Observed			Talamanca
	2001	2005	2011	
n ha^{-1}				
≤5	4.6	2.6	1.3	0.91
10	6.1	4.3	4.8	2.79
15	5.9	5.8	5.1	4.23
20	5.8	6.9	4.0	4.32
25	4.9	7.1	5.9	5.52
30	3.8	6.0	5.5	6.53
35	4.4	5.9	5.5	5.51
40	3.0	4.2	6.1	5.55
45	2.3	3.3	4.6	4.85
50	1.4	1.7	3.5	2.96
55	0.7	1.4	2.5	2.06
60	0.6	1.1	1.9	1.28
65	0.2	0.5	1.2	0.82
70	0.2	0.5	0.7	0.47

Year	Parameter	Estimation	SE
Coefficients of Weibull functions			
2001	κ	1.85234055	0.016673
	λ	27.3468131	0.012155
2005	κ	2.08723453	0.015827
	λ	34.3245211	0.010234
2011	κ	1.95627078	0.017280
	λ	35.3073091	0.011933
Talamanca	κ	2.1021697	0.0066311
	λ	35.1097897	0.0103219

Table 4 Diameter frequency distribution of *Cordia alliodora* in cocoa shade canopies in Central America. (Rolando Cerda and Eduardo Somarriba, unpublished)

D (cm)	Honduras	Nicaragua	Panama	Central America
≤5	5	8	12	25
10	21	70	565	656
15	66	85	974	1,125
20	115	104	939	1,158
25	169	110	904	1,183
30	150	167	831	1,148
35	117	81	492	690
40	91	81	389	561
45	62	39	279	380
50	34	22	148	204
55	16	4	90	110
60	18	6	58	82
65	12	0	29	41
70	3	1	22	26
75	9	1	18	28
80	1	0	9	10
85	1	0	7	8
90	1	0	3	4
95	0	0	2	2
100	0	0	0	0
105	0	0	1	1
110	0	0	0	0
115	0	0	2	2
120	0	0	0	0
Trees measured	891	779	5,774	7,444
Inventory area (ha)	81.96	34.51	79.35	195.82
Average D (cm)	29.32	25.11	24.29	24.93
Population (n ha^{-1})	10.87	22.57	72.76	38.01
Basal area (m^2 ha^{-1})	0.88	1.35	4.34	2.35

Timber yield of the Talamanca cocoa–laurel model

Laurel in the shade canopy of cocoa in Talamanca had a total population density of 47.81 trees ha^{-1}, including 23.5 trees ha^{-1} of harvestable size (D >40 cm); total basal area of 4.36 m^2 ha^{-1}, including 3.48 m^2 ha^{-1} in trees of harvestable size; and 48.23 m^3 ha^{-1} of total, over-bark stem volume, with 91 % (43.89 m^3 ha^{-1}) in trees of harvestable size. Laurel is predicted to yield 4.43 m^3 ha^{-1} year^{-1} of total timber volume in cocoa plantations in Talamanca. Both the annual harvest rate and the standing volume of timber were closely correlated with total basal area in the shade canopy (Fig. 6). Both laurel basal area and total volume are expected to increase over the 10 year simulation period. Stocking levels and current laurel D frequency distributions by farm have tremendous impacts on timber output over time: farms with few trees, concentrated in a few D classes, yield a lot less timber and experience more years without harvesting timber than farms with laurel at higher stocking and with trees of all sizes.

Table 5 Stem diameter increments and transition coefficients for naturally regenerated *Cordia alliodora* in the shade canopy of cocoa plantations, Talamanca, Costa Rica. Transition coefficients not adjusted for annual mortality by D class

D class	Mean periodic increment in D (I, cm year^{-1}) ± standard deviation)		Transition coefficient between adjacent D classes from year i to year i + 1 (not adjusted by survival rate)		
	Measured	Equation	Measured	Equation	By tree
0–5	4.71 ± 1.55	3.41	0.94	0.68	1
5–10	3.49 ± 1.21	2.84	0.70	0.57	0.58
10–15	3.28 ± 1.17	2.45	0.66	0.49	0.50
15–20	3.25 ± 1.11	2.15	0.65	0.43	0.50
20–25	2.71 ± 1.44	1.92	0.54	0.38	0.57
25–30	2.30 ± 1.51	1.73	0.46	0.35	0.42
30–35	1.22 ± 0.73	1.57	0.24	0.31	0.41
35–40	0.94 ± 0.60	1.42	0.19	0.28	0.29
40–45	0.96 ± 0.79	1.31	0.19	0.26	0.25
45–50	0.95 ± 0.79[a]	1.19	0.19	0.24	0.23
50–55	0.94 ± 0.41	1.08	0.19	0.22	0.18
55–60	0.78 ± 0.17[a]	0.99	0.16	0.20	0.16[b]
60–65	0.62 ± 0.44[a]	0.92	0.12	0.18	0.14[b]
65–70	0.46 ± 0.33	0.85	0.09	0.17	0.12[b]

[a] Interpolated values

[b] Projected using the rate of change in the transition coefficient between the 50–55 and 55–60 cm D classes

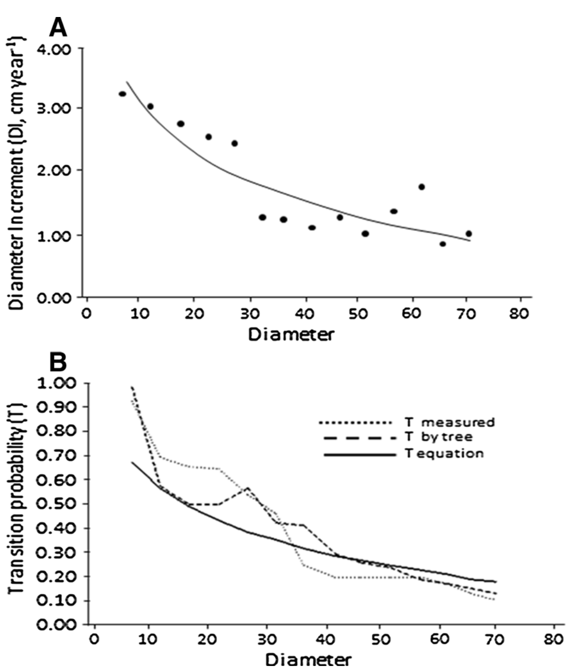

Fig. 2 Annual increment in stem diameter (DI) as a function of D (cm), and observed *versus* predicted mean annual diameter increment (I) and transition probability coefficients for naturally regenerated *Cordia alliodora* in the shade canopy of cocoa plantations, Talamanca, Costa Rica

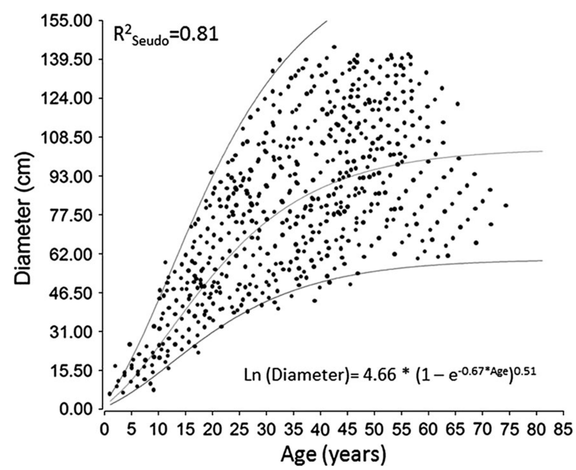

Fig. 3 Simulated diameter—age trajectories for individual *Cordia alliodora* trees in cocoa shade canopies in Talamanca, Costa Rica

Discussion

Cocoa production systems have been classified into six broad shade canopy types: open-sun cocoa, specialized shade, mixed shade, productive shade, rustic, and successional agroforests (Johns 1999, Moguel and

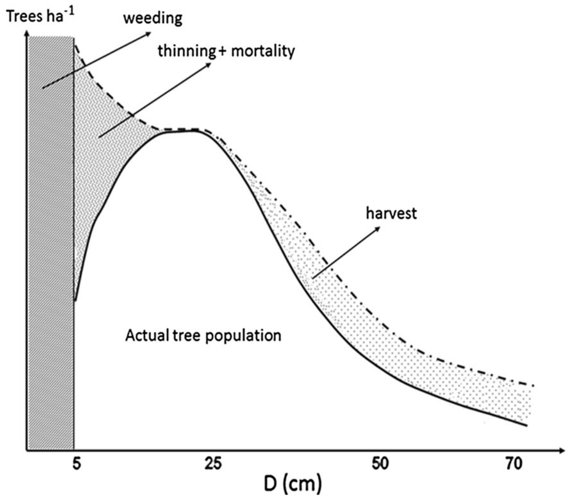

Fig. 4 The effect of weeding, thinning and harvest on the diameter (D) frequency distribution of *Cordia alliodora* in cocoa shade canopies, Talamanca, Costa Rica

Toledo 1999; Rice and Greenberg 2000; Somarriba and Lachenaud 2013). Timber trees are a frequent component in all but the first two shade canopy types. Cocoa–timber systems (a type of cocoa-productive shade) can in turn be classified into various sub-types, depending upon the species richness (mono-specific, multi-species), stand density (high, low) and origin of the timber trees (planted, natural regeneration, forest remnants).

The design and management of a cocoa–timber plantation requires the simultaneous consideration of multiple production goals set for cocoa, timber and other goods and services from the shade canopy. Farmer's goals, key determinants of the cocoa typology, can be expressed in terms of stocking rates of cocoa and shade canopy plants in the various cocoa–timber sub-types. Basal area (m^2 ha^{-1}) is proposed as the best stocking measure for cocoa plantations. Unfortunately, most plant inventories of cocoa plantations only report population density (e.g. trees ha^{-1}). In this study, population density did not vary accordingly to basal area and timber volume (harvested and standing) due to compensatory effects between tree size and population numbers. Consequently, widely different plantations in terms of population numbers can result in similar basal area or timber volume, and vice versa (Lobao and Valeri 2009; Sambuichi 2006). Population density estimates are also highly sensitive to the selection of the minimum tree stem diameter included in the inventory; 5 and 10 cm diameter are

Table 6 Growth (estimated from growth equation), survival, thinning, harvest and transition coefficients for a population of naturally regenerated laurel (*Cordia alliodora*) trees in cocoa plantations in Talamanca, Costa Rica

D upper class limit (cm)	%		Annual Survival S = 1 - [(T + H)/100]	I (cm $year^{-1}$)	Transition coefficients, adjusted by survival rate	
	Thinning (T)	Harvest (H)			Move on to next D class	Stay in same D class
5	3.8	0	0.962	3.41	0.66	0.33
10	14.0	0	0.860	2.84	0.49	0.44
15	14.5	0	0.855	2.45	0.42	0.50
20	9.0	0	0.91	2.15	0.39	0.55
25	7.32	0	0.927	1.92	0.36	0.60
30	3.34	0	0.967	1.73	0.33	0.64
35	0	4.39	0.956	1.57	0.30	0.67
40	0	3.21	0.968	1.42	0.27	0.70
45	0	4.99	0.95	1.31	0.25	0.71
50	0	6.55	0.935	1.19	0.22	0.73
55	0	8.95	0.911	1.08	0.20	0.73
60	0	19.41	0.806	0.99	0.16	0.68
65	0	19.52[a]	0.805	0.92	0.15	0.69
70	0	19.63	0.804	0.85	0.14	0.69

[a] Interpolated value

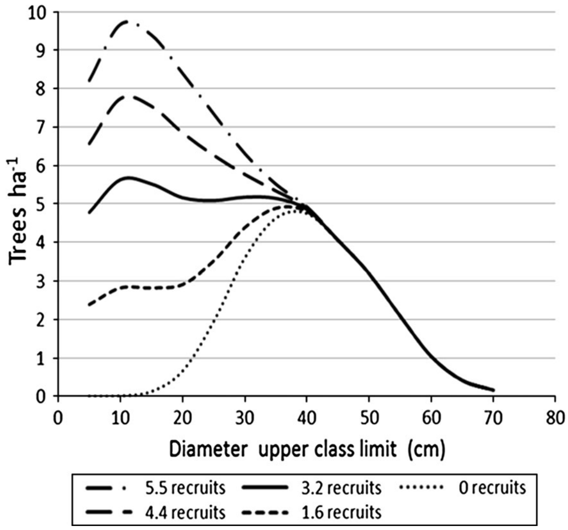

Fig. 5 Effect of different rates of recruitment of new individuals on the diameter frequency distribution of *Cordia alliodora* in cocoa shade canopies, Talamanca, Costa Rica. A rate of 3.2 recruits per year and per hectare is needed to project the frequency distribution observed in 2011 into the one observed in 2011

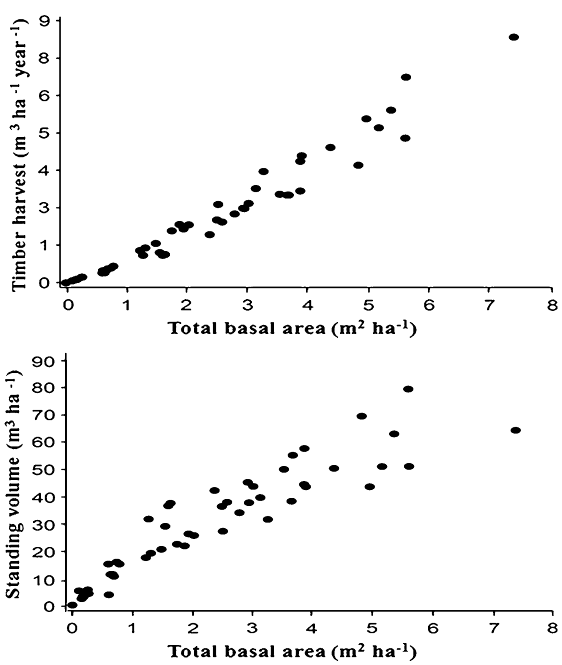

Fig. 6 Annual harvest rate, standing volume of timber and total basal area of *Cordia alliodora* in the shade canopy of cocoa plantations in Talamanca, Costa Rica

common selections, but some inventories report population numbers for plants D $\geq$2.5 cm. Since population density tends to be negatively correlated with plant size, small changes in minimum D will result in large changes in population density. Basal area, carbon, volume or biomass stocking are rather insensitive to changes in the number of small sized plants. Three-dimensional measures such as wood volume, aboveground biomass or carbon stored in aboveground biomass may be better proxy variables for stocking than basal area, but are harder (and more expensive) to estimate with precision. Canopy cover is closely related to these stocking measures and has negative impacts on cocoa yields (Clough et al. 2010), it may be estimated easily but precision will always be a consideration. Basal area (m^2 ha^{-1}) is easy and cheap to measure with great precision.

Basal area in different cocoa typologies in Talamanca decreased from 25.6 to 8.1 m^2 ha^{-1} in correspondence with a decreasing trend in structural complexity (Suatunce 2002). Other studies have reported basal area for the shade canopy only, between 8.0 and 13.6 m^2 ha^{-1} (Deheuvels et al. 2012). A study on the carbon stored in Central American cocoa plantations (Somarriba et al. 2013) reported mean basal area of 25.5 m^2 ha^{-1}, including 10.2 in cocoa and 8.2 in timber trees, and provided a breakdown of basal area (and other density estimates) for cocoa, timber, fruit, bananas, palms and other trees in the shade canopy. A calculation based on detailed inventories of 36 plots (1,000 m^2, 50 $\times$ 20 m, each), the allocation of population density and basal area between cocoa, laurel, bananas, others, shade canopy and plantation was: 591, 79, 189, 212, 480, and 1,071 plants ha^{-1}, and 10.15, 6.38, 5.96, 5.59, 17.93, and 28.08 m^2 ha^{-1}, respectively. Stand density parameters of cocoa plantations (cocoa + shade canopy) in Talamanca (population density, basal area, wood volume, biomass or carbon by surface area) are roughly similar to their homologues in Central America (Cerda et al. 2014); rustic cacao, known as cabrucas in Brazil, may attain higher basal areas than in Central America, with values ranging between 11.8 and 28.2 m^2 ha^{-1} in the shade canopy alone (Lobao and Valeri 2009; Rolim and Chiarello 2004; Sambuichi 2002, 2006; Sambuichi and Haridasan 2007); rustic cocoa plantations in Cameroon have basal areas of 32.7 $\pm$ 7.1 m^2 ha^{-1} (Bobo et al. 2006), other studies have reported 8–46 m^2 ha^{-1} (Bisseleua and Vidal 2008; Gockowski et al. 2010; Zapfack et al. 2002); low shade canopy basal area have been reported for both Ghana, 8.27 $\pm$ 1.7 m^2 ha^{-1} (Asase

et al. 2009) and Nigeria, 6.2 ± 2.1 m^2 ha^{-1} (Oke and Odebiyi 2007). Shade canopies in Indonesia range in basal area between 11.9 and 20.5 m^2 ha^{-1} (Bos et al. 2007; Kessler et al. 2005; Merijn et al. 2007).

Demographic information on naturally regenerated timber species in cocoa plantations is virtually inexistent. The basal area of laurel in the shade canopy in Talamanca (4.36 m^2 ha^{-1}) is similar to the basal area of timber species in cocoa shade canopies in Panama (4.34) and in Cameroon (4.5–6.7), but higher than in Honduras (0.88), Bolivia (0.22–1.13), and Nicaragua (1.35) (Cerda et al. 2014; Gockowski et al. 2010; Orozco 2005). The stable, humped, shape of the diameter frequency distribution of laurel in Talamanca is also similar to the ones observed in other Central American countries. All laurel frequency distributions had a hump around 30 cm and then a decrease towards large D.

Published diameter frequency distributions for all shade canopy plants (mixture of species with plants of all sizes) in cocoa plantations, show the same humped frequency distribution (or sometimes an inverse J-shaped distribution, well known in natural forests with multiple species and plants of all ages and sizes) observed for laurel in Talamanca (Asase et al. 2009; Asase and Tetteh 2010; Bobo et al. 2006; Kessler et al. 2005; Rolim and Chiarello 2004; Sambuichi 2002, 2006; Zapfack et al. 2002). The fact that the same shape of frequency distribution is obtained whether we look at the whole plant community or to individual populations (such as laurel in this study), indicates that it is the occupation of the space in the shade canopy by large trees that determines the shape of the frequency distribution.

The annual diameter increment of laurel in Talamanca was estimated from various approaches and using different data sets, including field and published data, plantations and natural regeneration in farm land, in pure stands or in mixed agroforestry systems, and in different site conditions (Alder and Montenegro 1999; Aristizábal-Hernández et al. 2002; Bergmann et al. 1994; Caycedo-Amador and van der Poel 1988; de las Salas 1981; Heuveldop et al. 1988; Hummel 2000; Navarro and Bermúdez-Cruz 2009; Ortíz and Riascos 2006; Ramírez et al. 2001; Ricker and del Rio 2004; Somarriba and Beer 1987; Somarriba et al. 2001; Chamorro-Trejos et al. 1994). Diameter–age and D increments as a function of D estimated for Talamanca are similar to laurel growth data published in literature (Fig. 7). Laurel grows rapidly in both D and total height early in its life cycle, with mean annual increments in both D and total height peaking at ages <4 years (Alder and Montenegro 1999; Caycedo-Amador and van der Poel 1988; Greaves and McCarter 1990; Heuveldop et al. 1988; Jaimez et al. 2013; Ortíz and Riascos 2006; Somarriba and Domínguez 1994; Somarriba et al. 1994, 1995, 1996; Somarriba and Beer 1987). This growth pattern may contribute to the successful establishment of laurel in the cocoa plantation. Laurel is a small seeded, wind dispersed species that "blanquets" the ground with seeds every fruiting season. With a good number of reproductive laurel trees in a cocoa plantation, laurel seeds explore every possible microsite in the plantation. At the appropriate micro-site the laurel seedling will grow quickly in height and D, over-top the canopy of cocoa, and will enter the population of laurel in the shade canopy. Some fast-growing laurel trees (sprinters) can reach 8 m in total height and 12 cm in stem diameter at 1.5 years of age (personal observations).

Some timber yield estimates are available for cocoa – planted timber systems with trees at higher population density than the one observed for naturally regenerated laurel in mixed shade canopies in Talamanca. For instance, in Costa Rica at 600 m altitude, cocoa with laurel planted at 278 trees ha^{-1} mean increment in total volume was 14.6 m^3 ha^{-1} $year^{-1}$ at age 7 years (Heuveldop et al. 1988). Volume increments of laurel in various agroforestry systems including cocoa, coffee, sugarcane and pastures varied between 8.76 and 20.29 m^3 ha^{-1} $year^{-1}$ (Somarriba and Beer 1987). Other studies in Talamanca, have reported 73.9 m^3 ha^{-1} for 11 years old laurel planted in new cocoa plantations, at 278 trees ha^{-1}; 113.8 m^3 ha^{-1} in fertile, alluvial soils, and in association with plantain, and laurel 10 years old at 69 trees ha^{-1}; and 47.7 m^3 ha^{-1} with 9 years old laurel planted at 204 trees ha^{-1} in mature cocoa plantations (Somarriba et al. 2001; Somarriba et al. 2012). Timber yields for laurel as a shade tree over coffee and cacao has been reported to yield between 4 and 6 m^3 ha^{-1} $year^{-1}$ (Beer et al. 1998). In Honduras, mean volume increment of the closely related *C. megalantha* planted at 185 trees ha^{-1} was 10.7 m^3 ha^{-1} $year^{-1}$ at age 14 years (Sánchez et al. 2002). In Talamanca, naturally regenerated laurel (this study) yields 4.43 m^3 ha^{-1} $year^{-1}$ of total timber volume. Annual timber yield is increasing as more

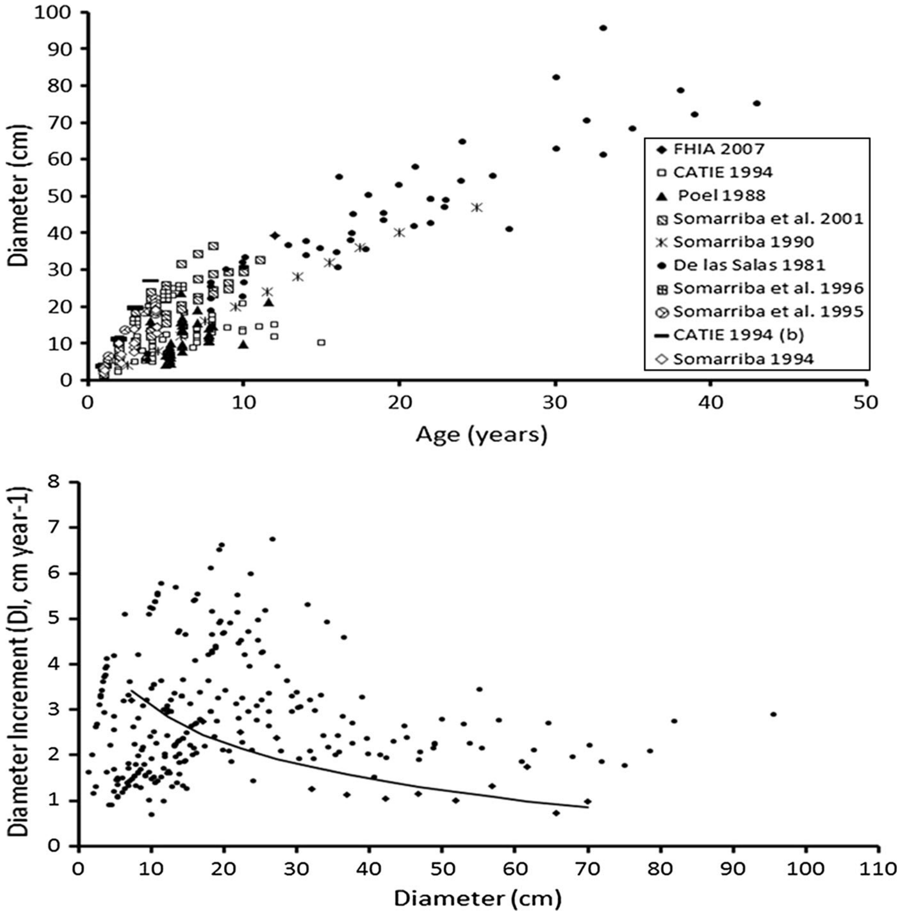

Fig. 7 Age, diameter and increment data for *Cordia alliodora* published in the literature and from this study (line)

trees enter the harvestable class. Even with current harvest rate of 4.43 m^3 ha^{-1} $year^{-1}$, the stock of timber (both total and harvestable volume) is increasing, suggesting that a higher harvest rate is possible without compromising the sustainable production of timber i.e. without reducing the current stock of laurel in the cocoa shade canopy. The steady increase in basal area of laurel in the shade canopy between 2001 and 2011 may be taking place at the expense of reductions in the basal area of non-timber species.

This study indicates the need for more systematic research looking at the population size and structure, growth, recruitment, survival, thinning and harvest of timber species in cocoa shade canopies. The projection model developed for Talamanca is based on solid estimates of population density, diameter frequency distribution, diameter increments and harvest of timber. But more focused research is needed to understand recruitment and thinning rates, to be able to estimate true mortality of laurel by size class. Cocoa–timber systems based on size-structured populations (such as laurel in Talamanca) need moderate plantation size (say $\geq$3 ha) to maintain a big enough population to accommodate trees of all sizes and yield acceptable, regular outputs (annual?) of timber. More research is needed to elicit farmers' management rules determining the recruitment, thinning, and harvest rates of laurel. This study indicates that re-measuring laurel trees in permanent sample plots in intervals greater than 4 years is excessive given the fast diameter growth rates of the species; a 2–3 year re-measurement interval seems more appropriate for laurel in Talamanca. Timber is usually highly regulated and subjected to numerous cultural and social beliefs and values that limit the widespread management (sustainably) and use of timber trees in farm fields. We need to document the legal, cultural and social frameworks that limit the widespread use of timber as productive shade over cocoa (worldwide, by region, by major cocoa producing countries).

Conclusions

This study shows in quantitative terms the significant contribution of timber in the shade canopy of cocoa to annual income (use or sale of timber) and family savings (timber in standing, harvestable trees). For instance, in Talamanca, laurel yields 4.43 m^3 ha^{-1} $year^{-1}$ of timber, equivalent to an annual additional income of 265 US\$ ha^{-1} $year^{-1}$ [(assuming that 50 % of total standing volume is saleable, and a price of 120 US\$ m^{-3} for standing laurel timber at the farm (José Alberto Moore, local chain saw operator, personal communication, 31 August 2013)]. In addition to the cash flow, standing, harvestable laurel trees (43.89 m^3 ha^{-1}) amounts to 2,633 US\$ ha^{-1}. Basal area is recommended as the stand density measure of choice for the analysis and design of cocoa plantations.

Acknowledgments This research was funded by CATIE-MAPNoruega and FTA/CATIE. Thanks to Natalia Arce and Hernán Andrade for re-visiting with us the data bases of inventory of cocoa plantations in 2005. Maureen Arguedas compiled the diameter, age and growth data reported for laurel in the technical and scientific literature. One anonymous reviewer provided useful constructive criticisms and sound recommendations that helped to improve the quality of the manuscript.

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